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RESONANT VIBRATION OF STEEL STACKS

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SYNOPSIS

Shortly after their completion, the steel stacks of Moss Landing Steam Plant were excited to violent vibrational movement by a steady wind of moderate velocity, although these stacks were conservatively designed in accordance with commonly accepted practice and were capable of withstanding as a static force the drag from a wind of several times the velocity which occurred. Investigation indicated vibration was caused by periodic forces developed during the formation of Karman Vortices in the air stream around the stacks. This paper discusses the character and magnitude of the disturbing aerodynamic forces, investigation and studies made and the design of corrective measures installed to protect the stacks from similar future disturbances.

Resonant Vibration of Steel Stacks

From the early days of civil engineering, generally accepted practice has been to design bridges, buildings and other structures to resist wind on the basis that wind forces could be replaced for design purposes by some equivalent system of static loads.

For the past 50 years, the rapid growth of airplane design has led to widespread research both theoretical and experimental with respect to aerodynamic forces. However, the generally satisfactory performance of bridges, buildings and structures designed to resist wind on the basis of static loadings has not as yet led the structural designer to make use, to any great extent, of the developments in the field of aerodynamics.

The dangerous effects that can occur to machine elements or structures if their natural period of vibration happens to be in resonance with a periodic exciting force, even though small in magnitude, has long been recognized. That a wind of moderate velocity can exert periodic forces upon structures or bridges with disastrous results has not been fully appreciated. It required the collapse of the Tacoma Narrows Bridge, to focus the attention of bridge designers on the importance of aerodynamic forces.

This paper describes unforeseen serious vibrations at low wind velocities experienced by tall steel stacks, conservatively designed in

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accordance with accepted practice for high wind velocities and for the effects of possible earthquake action. The investigations into the cause of these phenomena, the corrective measures taken, and the conclusions drawn from this occurrence with respect to stack design are described.

General

The Moss Landing Steam Plant of the Pacific Gas and Electric Company is situated on the eastern or inshore side of Moss Landing Harbor on Monterey Bay, about 100 miles south of San Francisco. The initial plant, which consists of three 100,000 kw steam turbine generators, six boilers, and associated auxiliaries, was completed in 1950. An extension to the plant, consisting of two 100,000 kw steam turbines, two boilers and associated auxiliaries, was completed in 1953.

This paper deals primarily with the stacks of the initial installation of which there are six, one for each boiler. The arrangement of the stacks for the three initial units, with respect to the plant, is shown in Fig. 1. Details of a typical stack are shown in Fig. 2.

The stacks were designed to be self-supporting under the following considerations:

Wind load of 25 psi on projected area or seismic force of two tenths gravity. The wind load governed the design.
The computed maximum compressive stress in the steel shell on this basis was 6,700 psi.
Ratio of diameter to thickness of steel shell not greater than 500 to 1.
Ratio of any given diameter to height of stack above not less than 1 to 12.
Stack plates are butt welded throughout.

Observations

At Moss Landing during the late summer and fall, a moderate wind frequently springs up about noon, blowing from the open ocean on the west across the flat unobstructed shore line and the plant site, and dying out about 5 o'clock in the afternoon. While the velocity may vary from day to day and from hour to hour on a given day, this wind is characterized by very uniform velocity, free from turbulence, for appreciable periods of time.

Late in the afternoon on October 5, 1949 with the steel shells for stacks Nos. 2 and 3 completed but unlined and a moderate wind as described above, a slight breathing or ovalling of short duration was noticed about halfway up the straight section of stack No. 3.

On the following afternoon with a wind from slightly north of west at an estimated velocity of 25 mph, stack No. 3 again ovalled or breathed in and out for an appreciable distance above and below the mid-height of its straight section. No definite measurements were taken but the movement was very noticeable and probably amounted to several inches. It had a definite cadence estimated at 88 times per minute. The base of the stack appeared perfectly rigid and there was no noticeable movement of the top of the stack. A spreader spider was

immediately installed inside stack No. 3 about at the mid-point of its straight section where movement had been the maximum.

On the next afternoon, October 7, 1949, a similar wind from slightly south of west at a somewhat higher velocity possibly 30 to 35 mph caused no breathing or vibration of stack No. 3. However, on this date the top of adjacent stack No. 2, which had neither breathed nor moved noticeably heretofore, swayed back and forth about 4 to 6 in. in regular cadence. This swaying affected stack No. 2 throughout its entire height and there was definite evidence of spalling of the grout under the base ring and a few anchor bolts could be tightened up about 1/8 turn. In no case was it possible to tighten two adjacent anchor bolts. The next day two 3/4 in. steel cable guys were installed on opposite sides of stack No. 2 about 64 ft down from the top leading to two dead-men ground anchors, one northwest and the other southwest of this stack.

Preparations were made to take instrument readings of stack movements and an anemometer was installed at the top of stack No. 2 to record wind velocity. The next observable movement occurred on the afternoon of October 18, 1949, when the most violent movements were experienced. Summarizing conditions at this time, an internal spreader spider was in place at about the mid-height of the straight section of stack No. 3 and a 1/4 in. Monel painter's trolley line was attached at the top of this stack on the southwest side but was hanging loose. Stack No. 2 had no internal spider but had two 3/4 in. steel guy cables to dead-man anchors as described above. The steel shell of stack No. 1 was completed except for the top 8 ft high ring, contained no internal spiders and was not guyed. Gunite linings had not been started in any of the stacks.

The wind and attendant swaying of the stacks commenced about 12:45 P.M. and continued until shortly after 4:00 P.M. The anemometer, installed on the top of stack No. 2, failed to register. Wind velocity was estimated to be between 30 and 40 mph at ground level and was steady in both direction and velocity. Its direction was from slightly north of west. Stack No. 3 started moving first. The erector crew immediately attached the 1/4 in. Monel line to a box car which was located near the base of stack No. 1. This was done before instruments were set up to measure the movement. Visual observation indicated that fastening this line to the box car restricted the movement, although it is impossible to estimate to what extent. Stack No. 2 started moving a few minutes after stack No. 3. The paths described by the top of both stacks were elongated ellipses, the major axis being north and south or generally at right angles to the direct of the wind. The amplitudes of movement were erratic during the afternoon. Movement would at first be slight, then increase to a maximum which would continue for various lengths of time and then die down. Movements of the stacks were independent of each other. First one stack would move and then the other. Frequently both were swaying. At times, movement was in phase and at times out of phase. The length of time of any period of movement was varied and did not follow any specific pattern. However, the frequency was constant throughout at 72 to 74 cycles per minute. Movements of the top of the stacks at various times during the afternoon were measured with transits and are recorded in detail in Table 1. The maximum observed total sway was over 32 in.

The guy wires on stack No. 2 and the painter's trolley on stack No. 3 absorbed, by stretching, whipping and movement of their anchorages, appreciable amounts of the vibrational energy of the stacks, thus limiting amplitudes of vibration. These lines had to be pulled up several times during the afternoon because of stretch. The force transmitted through the painter's trolley rocked the box car to which it was attached so violently that this line was transferred to a heavy caterpillar crane.

There was appreciable vibration of the base of the stacks and of the concrete foundation. The stack mat at the anchor bolt ring moved vertically by as much as 0.01 ft double amplitude. On the north side of the foundations of both stacks Nos. 2 and 3, the earth cracked over the edge of the foundation mat. Several bolts on the north and south sides of both stacks were loosened, sufficiently in a few cases that the nuts could be turned by hand. During periods of maximum stack movement, there was a noticeable squeaking noise at the tops of the bolts. Pieces of grout up to 3 in. long by 1-1/2 in. wide by 5/8 in. deep flaked out from between the stack base and the top of the concrete foundation at the north and south sides of both stacks Nos. 2 and 3.

Stack No. 1, at this time only 8 ft less in height, showed no appreciable vibration or movement. Movements ceased when the wind dropped shortly after 4:00 P.M. About 4:30 P.M., a squall with heavy rain came up, during which time it is estimated that the wind blew even harder than at any time earlier during that afternoon. This wind lasted only a short time, but during this time, there was no observable movement of any of the stacks.

Following these violent movements, both stacks Nos. 2 and 3 were thoroughly examined. A visual check did not indicate any cracked or broken welds. Welds located at critical points were magnafluxed both inside and outside. This check indicated that none of the welds had been cracked. Two coupons taken at random indicated that full penetration was obtained in the welding. Diameters of the stacks were measured at a number of locations. Maximum variations from specified diameter were plus 1-1/4 in. and minus 1-1/2 in. Stacks were checked for plumbness at a time when there was no wind or sun, and the maximum out of plumb found was only 0.46 ft. These examinations indicated that, despite the rough treatment, the stacks had suffered no permanent distortion or damage.

As a temporary protective measure during the remainder of the construction program and until permanent corrective measures could be installed, all stacks were guyed three ways and at two levels immediately following erection of the stack shell. Also, additional steel stiffener rings were welded to the stacks at intervals of 16 ft throughout the cylindrical portion to prevent ovalling. These consisted of 6 in. by 4 in. by 1/2 in. circumferential angles welded to the stack shell with the 4 in. leg out and turned down.

Aerodynamic Forces

Analysis indicated the Moss Landing stacks compared favorably in strength and stiffness with numerous stacks throughout the country which had performed satisfactorily. The rhythmic character of the

movement and its dependence upon a particular wind condition directed the study to their aerodynamic characteristics.

The drag of a cylinder moving at uniform velocity through a fluid is the sum of frictional forces and of energy losses resulting from eddies set up in the fluid. Between Reynolds' numbers of approximately 1,000 and some larger number called the critical value of Reynolds' number, eddies are shed in a regular pattern from alternate sides of the cylinder. For a nonoscillating cylinder or for a cylinder which vibrates through a small amplitude relative to the diameter of the cylinder the approximate relations between

- h - The distance between eddy paths
- ℓ - The distance between eddies in a single path
- D - Diameter of the cylinder
- V - Velocity of the cylinder
- f - Frequency of eddy formation

are as follows:

$$\frac{h}{\ell} \approx 0.3, \quad \frac{h}{D} \approx 1.3, \quad \frac{\ell}{D} \approx 4.3 \quad \text{and } f \approx 0.2\frac{V}{D} \tag{1}$$

The dimensionless ratio $S = \frac{fD}{V}$ is called the Strouhal number after the man who first investigated these eddies in 1878.

While an eddy is forming, the fluid on the side opposite the eddy has a higher velocity as it passes the cylinder. In accordance with Bernoulii's theorem, this increased velocity must be accompanied by a decrease in pressure. There is consequently a lift or force exerted upon the cylinder acting in a direction away from the side on which the eddy is forming. Since the eddies form alternately on opposite sides of the cylinder, it is subjected to an alternating force of a frequency equal to the frequency of formation of the eddies.

The lift or lateral force exerted during the formation of vortices may be expressed by the term

$$\text{Lift} = C_L \, \rho \, \frac{V^2}{2} \, D \tag{2}$$

in which C_L = Coefficient of lift

ρ = Density in appropriate mass units

It is common in investigations involving periodic vortices to assume that C_L varies as a simple harmonic function. Experimental or analytical determinations of C_L max are rather limited. Steinman (2) showed analytically that for an infinitely long, nonoscillating cylinder C_L max = 1.71. Ruedy (3) derived analytically C_L max = 0.93, and quotes experimental values of C_L varying from 0.61 to 1.05. Computation of C_L from experimentally determined values of pressure reduction along the sides of cylinders indicate C_L = 1.13 at R = 962,000 (4). The above values are the maximum values of C_L in a single cycle.

Above the critical value of R the boundary layer ceases to be laminar and becomes turbulent. This causes the breaking away point of the eddies to move backward along the body reducing the size of the eddies and the width between eddy trails. Since the vortex trail is stable only for a constant ratio of $\frac{h}{\ell} \approx 0.3$, reduction in the width between eddy trails h also reduces ℓ and causes a corresponding sharp increase in the frequency and the Strouhal number as shown in Fig. 3.

The actual range of the Strouhal number is not large. Den Hartog (6) gives the range of S to be between 0.18 and 0.27 for cylinders. A mean value of S = 0.22 was used generally in the following analysis. Relf (5) and Goldstein (7) show that above this critical range the flow becomes turbulent and formation of vortices ceases to be periodic.

The critical Reynolds' number is not a sharply defined value, but extends over a very considerable range depending upon the turbulence in the air stream and upon the relative smoothness of the cylinder. Experiments by Relf and Simmons (5) indicated that the critical range lies between R = 200,000 and R = 500,000. Experiments in the wind tunnel at Gottingen indicated the critical range to be of the order of R = 500,000 to 1,000,000. However, as illustrated in Fig. 3 actual experience with large diameter stacks, Pagon (4) and Moss Landing, has shown formation of periodic vortices at $S \approx 0.2$ for Reynolds' numbers of nearly 5,000,000.

Resonance of Stacks with Periodic Aerodynamic Forces

The alternating forces exerted upon an elastic cylinder attendant to the forming of periodic vortices in the air stream may cause the cylinder to vibrate either by ovalling, that is, vibration as an elastic ring or by swaying, that is vibration as an elastic cantilever. Both types of vibration were noted at Moss Landing, the first movement being ovalling.

The lowest or fundamental frequency of vibration of an elastic ring may be reduced for a steel cylinder to

$$N = 41{,}000 \frac{t}{D^2} \tag{3}$$

Where

N = frequency in cycles per minute

t = thickness of cylinder stack shell in inches

D = diameter in feet

Solution of this expression for the Moss Landing stacks shows a natural frequency of 120 cycles per minute for the 3/8 in. plate and 100 cycles per minute for the 5/16 in. plate sections of the stack.

Since the pressure reductions during formation of vortices occur alternately on opposite sides of the stack, periodic vortices will excite ovalling at double their own frequency as illustrated in Fig. 4.

Karman vortex frequency for a wind velocity of 25 mph wind and an 11.4 ft diameter cylinder would be 42 cycles per minute at a Strouhal number of 0.22. Twice this would be 84 cpm which is reasonably close

to the frequency of 88 cpm observed on October 6. It is believed pressure variations from vortices forming at a Strouhal number of $S \approx 0.22$ excited near resonant ring vibrations of these stacks causing the ovalling observed.

Swaying, that is vibration as an elastic cantilever, occurred on October 7, and again on October 18, the amplitude on the latter date being much greater and the record more completely documented. The wind velocity on October 18 at near ground levels was estimated to be 30 to 40 mph. The frequency of the vortices computed from Equation 1 for a wind velocity of 40 mph and a stack diameter of 11.4 ft is 68 cycles per minute at a Strouhal number of 0.22. The observed frequency of vibration for stacks 2 and 3 was 72 to 74 cycles per minute which is in reasonably close agreement with the value derived above.

Rigorous computation of the frequency of vibration of these stacks as contilevers would be extremely complicated because of the variable moment of inertia and variable mass. However, reasonably close approximations can be made by several methods such as Rayleigh's method or by the following approximation:

It may be shown that for inch-pound units, the fundamental frequency of a uniform cantilever is approximately

$$f = 11.8 \sqrt{\frac{K}{M}} \tag{4}$$

Where

f = Natural frequency in cycles per minute

K = Stiffness in terms of total force uniformly distributed over length required to deflect cantilever 1 in. at the top

M = Total mass $\frac{W}{g}$ when W equals weight in pounds and g is acceleration due to gravity = 386 inches/sec^2

For the unlined stacks K was computed to be 12,400 lbs/inch, W was approximately 150,000 lbs and f = 67 cycles per minute.

This frequency includes the effect of the variable stiffness but does not include the effect of the distribution of mass due to variable plate thickness and flared base. The actual distribution of mass would cause a slightly higher natural frequency and rotation of the concrete foundation would cause a lower natural frequency.

The computed frequency of the vortices and the computed natural frequency of the stacks were in reasonable agreement with the observed type of motion and observed frequency of stack swaying. It was concluded that swaying of these unlined stacks was due to resonant vibrations actuated by the forces attending the formation of periodic vortices in a steady air stream.

Calculations using available data with respect to the elastic properties of the Haydite-Lumnite lining indicated that the natural frequency of the stacks after lining would be somewhat lower than the unlined

stacks. Consequently after lining. the stacks would be resonant with winds of somewhat lower velocities which might occur more frequently.

Since the internal friction or damping of concrete is many times that of steel, it was anticipated that the lined stacks would have appreciably more damping than the unlined stacks. The logarithmic damping decrement (8) of the lined stack was computed to be $\delta = 0.08$ working from available data (9) on the damping characteristics of concrete and ignoring foundation damping. While this amount of damping would limit vibration, computations indicated the amplitude would be excessive. Further analysis showed that variations in thickness of the lining within the limits indicated by stresses in the shell and foundation under earthquake loads would not change the damping decrement sufficiently to bring the computed amplitudes of vibration within acceptable limits.

Because of location and climatic conditions the Moss Landing site is subject to steady, nonturbulent winds of near resonant velocity a number of times during a year. Since conditions were conducive to the formation of vortices, it was considered probable, unless corrective measures were undertaken, that resonant vibration would again occur with probable damage to one or more stacks resulting in a lengthy outage of their respective boilers. Consequently complete protection against the effects of periodic vortices was considered essential.

Corrective Measures

Resonant vibration of elastic structures may be limited or prevented by several different methods:

a. Remove the source of vibration
b. Change the resonant frequency of the elastic structure so that it is no longer resonant with the driving forces
c. Provide damping to absorb and dissipate the energy of vibration

A system of fins or spoilers on the stack to prevent the formation of vortices was considered. Some experimental work had been done on submarine periscopes at $R \approx 4{,}000$ which indicated that spoilers to be effective would have to extend about one diameter from the cylinder. Such spoilers attached to the upper portions of the stacks would have increased the maximum wind resistance sufficiently to overstress the stack shells and foundations. Other references indicated that possibly smaller spoilers would be effective but this hypothesis is unsupported at present by experimental data and until proved could not be depended upon. Since reliable data on the effect of spoilers or on their required size could not be obtained, this procedure was eliminated.

The maximum known wind velocity, at which periodic vortex induced vibration of stacks has occurred, is approximately 60 mph. It is believed that close to the earth's surface winds having a velocity in excess of approximately 60 to 65 mph are sufficiently turbulent to prevent formation of periodic vortices for cylinders of a diameter such that their Reynolds' number is in excess of 1,000,000.

From this, it has been concluded that stacks should be free of vortex induced vibration if made so stiff that their fundamental frequency as a cantilever or twice their fundamental frequency as a ring were

equal to or greater than the frequency of eddy formation for a wind velocity of 70 mph computed for a Strouhal number of 0.22 (80 mph if S is selected equal to 0.19).

The arrangement of the stacks is such that a conventional guying system for each stack, using normal size guy wires, would seriously interfere with normal plant operations at ground level. Furthermore such guys would not theoretically increase the natural frequency of the stacks sufficiently to eliminate the start of resonant stack movement.

Since the guyed stacks would be an elastic system, under resonant periodic forces resulting from the wind they could be set into vibration which theoretically would increase until sufficient damping developed from stretching of the guys to limit the vibration at some value. Thus during each period of vibration the guys would have to be tended to remove the stretch caused by the vibration to prevent excessive amplitude of movement. This would suffice for temporary protection, but was not considered satisfactory as a permanent measure.

Methods of increasing the stiffness of the stacks sufficiently to make them nonresonant with winds below 70 mph by portal bracing and by rigid bracing to the power house did not appear practical or economic because of the difficulty of accommodating thermal movements of the individual stacks.

Since increasing the stiffness of these stacks sufficiently to eliminate resonance did not appear practical or economic, attention was turned to damping systems in which the energy input of the periodic forces would be absorbed.

Swaying would not be entirely eliminated by the damping system since energy can be dissipated by the dampers only when there is movement. However, by providing the proper amount and type of damping, the amplitudes of vibration would be limited to values well below normal deflections in high winds. Limitation of the double amplitudes of vibration to about 2 in. at the top was found entirely practicable and was considered desirable, both from the psychological effect and to protect the gunite lining installed to prevent corrosion of the stack shell from cracking or stresses which would shorten its effective life.

It may be shown that the energy, W, per cycle pumped into an elastic cantilever by a simple harmonic force applied uniformly along the length of the cantilever and having a maximum value of ± w per unit length acting in resonance with the vibration of the cantilever is:

$$W = \frac{2\,\pi}{5} \quad y_o \quad wL \tag{5}$$

where W = Energy added per cycle

y_o = Elastic deflection of end of cantilever under uniform static load of w per unit length

L = Length of cantilever

For stacks, w is equal to the lift developed during formation of the vortices, i.e.:

$$w = C_L \; \rho \; \frac{V^2}{2} D \tag{2}$$

As previously outlined, the value of C_L is only imperfectly established. On the basis of available data and considering circulation over the top of the stacks, a value of $C_L = 1.0$ was assumed. Computation of the fundamental frequency after lining gave a value of 55 cpm for an assumed modulus of elasticity of 2,000,000 psi for the 2 in. gunite lining. This would correspond to a wind velocity of 32 mph for $S = 0.22$ or of 37 mph for $S = 0.19$.

A wind velocity of 40 mph was selected for design of the damping system for which $w = 45.6$ lb per ft of height of the cylindrical portion of the stack and from Equations 2 and 5.

$$W = 1070\, y_0 \text{ ft-lb per cycle} \tag{6}$$

A damping system employing viscous dampers, such as are used in hydraulic shock absorbers, could have been used. While viscous damping is smoother, dry friction damping is more effective in limiting small amplitudes of motion at low velocities. Also, it was believed that a friction type damper system would require less maintenance and could be installed in a simpler arrangement. The final design was prepared using friction dampers.

The arrangement of the damping system is shown in Fig. 5.

For each group of three stacks, two sets of horizontal trusses are provided which are pin connected to the stacks. These trusses will permit vertical movement of any individual stack, but force the three stacks to move in unison in the north-south direction. Crossed diagonals are provided with friction connections at their lower ends to form the damping system in the north-south direction. The diagonals are not connected to each other where they cross. The friction forces in the connections are not large enough to restrict thermal expansion of any stack.

Long struts with friction connections are provided extending from the two end stacks to the boiler supporting structure. The struts with the horizontal trusses form the damping system in the east-west direction.

For movements in a north-south direction in the plane of the stacks, the lengths of the diagonals change by some amount "x" which is proportional to the deflection, "y_0", of the tops of the stacks. These values for the limiting deflection selected for the Moss Landing stacks are shown in Fig. 6. This change in length of the diagonals causes slippage of the friction connections at their lower ends. Slippage at each friction connection = $(x - \Delta x)$ where Δx is the elastic shortening of the struts for the frictional force developed at each connection. Then total energy, F, dissipated in 1/4 cycle by four dampers for three stacks;

$$F = 4\,(x - \Delta x)\, P \tag{7}$$

where P is frictional force of each damper. By selecting P properly the energy dissipated in each cycle could be made equal to or larger than the energy put into the system by the wind. Similarly in the direction perpendicular to the plane of the stacks, energy is dissipated in the dampers at the boiler house. It was convenient using commercially available springs and friction materials to set the dampers so they would dissipate about 10 per cent more energy per cycle than would be

put into the stacks by a wind of 40 mph. There will also be some additional damping provided by the stack lining and the working of structural connections.

An available industrial friction material with a nominal coefficient of friction of about 0.45 was chosen for the friction dampers. It was found that the nominal coefficient of 0.45 was based on dynamometer tests of kinetic friction set up in the manner of common industrial usage with braking at high speed and consequently at high temperatures. Tests indicated that at low speeds the coefficients of both static and kinetic friction would be about half this value. A coefficient of friction of 0.2 was used in the design.

All structural members and connections are designed for more than three times the design friction forces without exceeding allowable working stresses. This was done to provide a factor of safety should the coefficient of friction in the friction material increase from the value of 0.2 at low loading velocities to the value of 0.45 or higher, furnished by the manufacturer as the nominal coefficient of friction for this material.

Vibration Tests

In the foregoing analysis, it was shown that on a theoretical basis the installation of gunite linings 2 in. in thickness could not be depended upon to reduce stack vibrations to acceptable safe limits under the conditions which exist at Moss Landing. However, there was practically no experimental data to substantiate this conclusion.

The Pacific Gas and Electric Company suggested that full scale tests be made on the Moss Landing stacks to determine the actual natural periods of the stacks in both unlined and lined condition, together with the damping characteristics present in both conditions.

Although stacks Nos. 2 and 3 were the ones that had shown excessive movement under wind forces these stacks were placed in service almost immediately after the completion of their linings and it was decided to make the tests on stack No. 6.

For each test the stack was deflected a predetermined amount and suddenly released. The stack was tested in a north-south direction and in an east-west direction. For each test the frequency of vibration and the decay curve were established.

To measure the vibration SR-4 strain gages were mounted just above the bell since this was the point of maximum stress. A gage located on the axis parallel to the movement of the stack was attached to a Baldwin strain indicator and a motion picture was taken of the movement of the needle.

A supplementary method employed engineers' transits. Two sections of level rod were attached in a horizontal position to the top of the stack, one extending north and south for the tests in the north-south direction and one extending east and west for the tests in the east-west direction. Several transits were trained on a rod reading approximately on the center line of the stack. When the stack was deflected and released, each transit man counted the number of cycles from the time of release until a predetermined amplitude was coincident with his line of sight.

These data established a number of points along the decay curve, and from them the decay curves of each test were plotted.

To deflect the stack in the north-south direction a wire line was connected horizontally between the tops of stacks Nos. 5 and 6. A downhaul line was attached near the midpoint of the horizontal line, which, when loaded, pulled the stacks together. A strain link was provided in the line near stack No. 6 to measure the load required to deflect the stack. A quick release hook tripped from the ground released the stack sharply permitting it to vibrate freely and with a minimum of interference.

Stack No. 6 was deflected in an east-west direction by pulling it with a line attached to the boiler house.

The first series of tests were made on the unlined shell of stack No. 6 on January 6 and 7, 1950. The lining of stack No. 6 was completed on March 17, 1950 and the second series of tests was made on April 17, 1950. The weather for both series was satisfactory with little or no wind.

The observations of the decay of vibration by transit and damping decrements computed from these observations are given in Tables 2A and 2B.

The observations of the decay of vibration by motion pictures of a strain indicator attached to SR4 gage and damping decrements computed from these observations are given in table 2C. Only one successful observation was made by this method on the unlined stack and five successful observations were made on the lined stack.

It is mathematically convenient to investigate damping by assuming that for short intervals, at least, it approximates viscous damping. For true viscous damping the amplitude of each cycle has a constant ratio to the amplitude of the preceding cycle. The ratio of the reduction in amplitude to the amplitude which is termed the damping decrement can be expressed as:

$$\delta = 1 - \frac{y_{n-1}}{y_n} \qquad (8)$$

And for n number of cycles:

$$\delta = 1 - \left[\frac{y_n}{y}\right]^{\frac{1}{n}} \qquad (9)$$

The average damping decrement for the steel shell was found to be 0.029 and the average damping decrement of the stack complete with lining was found to be 0.045, which is less than the estimated value of 0.08.

Values of the damping decrement were quite erratic in the various tests. There was indication it was not constant, which would be the case for true viscous damping, but increased with amplitude. Averaging all test results for the lined stacks indicates an average damping decrement in the lined condition varying from $\delta = 0.02$ at zero amplitude to $\delta = 0.068$ at about 4 in. amplitude. This trend if extrapolated gives a value of $\delta = 0.15$ at 10 in. amplitude.

The fundamental frequency of the completed stack had been computed at 55 cpm assuming E = 2,000,000 psi for the gunite lining. The actual

frequency found by test was 49 cpm, which corresponds with the frequency of eddy formation for a wind velocity of 29 mph at a Strouhal number of 0.22. The input energy W per cycle for this wind velocity would be W = 556 y_o ft-lb per cycle where y_o is the vibrational amplitude of the top of the stack in inches.

Computation of the stiffness of the stack after lining from the observed frequency indicated that the lining increased the stiffness by only about 5 per cent.

The energy dissipated by viscous damping per cycle, ΔW, is given by the expression

$$\Delta W = 2 \delta W_o \tag{10}$$

where

δ = logarithmic damping decrement

W_o = total accumulated energy at the end of any cycle which is equal to potential energy at point of maximum deflection.

For the lined stack based upon the stiffness obtained in the tests

$$W_o = 216 y_o^2 \text{ ft-lb} \tag{11}$$

for any amplitude of vibration y_o at the top in inches.

Then the energy dissipated per cycle

$$W = (2\delta)(216 y_o^2) \tag{12}$$

Under steady state excitation, vibration of these stacks as individual structures would build up until the energy dissipated in each cycle of vibration just equaled that pumped into the stack by the wind forces. The energy pumped into the stack per cycle at various wind velocities and that dissipated per cycle for various amounts of damping are shown graphically in Fig. 7.

The energy dissipated by damping at δ = 0.045, the average value found in tests on the lined stack, is so small that, as shown, the resulting amplitude of vibration would be so large as to destroy the protective gunite lining and probably result in failure of the stack shell. As noted, there was some indication that the damping increased with amplitude, possibly reaching δ = 0.15 at an amplitude of about 10 in. Assuming this amount of damping did develop it would limit vibration of the stacks to an amplitude of about 9 in. for a 29 mph wind. Continued vibration of this amplitude would undoubtedly cause severe cracking of the lining.

The above analyses have been based upon steady state conditions. The wind, even under the very uniform conditions of Moss Landing, is never perfectly constant. The time required to build up to excessive vibrational amplitudes was also investigated. The energy stored in the stack at its point of maximum deflection at any cycle of vibration is equal to the potential energy at the same point of the previous cycle, plus energy pumped in during the cycle, less energy dissipated by damping during the cycle.

Computations indicated that for a damping decrement increasing uniformly from $\delta = 0.02$ at 0 in. to $\delta = 0.15$ at 10 in. amplitude, vibration of these stacks without an external damping system would build up very quickly, reaching almost maximum amplitude within 20 sec. Steady state winds of several times this duration and of critical velocity may be expected many times in the life of these stacks. Also investigations, as reported by Steinman (2) have shown that once movement has started eddy formation tends to be self-exciting and will continue at constant frequency, even though stream velocity changes appreciably.

This analysis has assumed the force developed by the formation of the vortices was uniform from top to bottom of the stack. This is conservative since possibly vortices are not formed near ground level. However, it may be shown from the deflection curve of the stack that the energy input from the bottom third, assuming uniform load, amounts to only about 4 per cent of the total energy input in any one cycle.

This test program showed that damping in the gunite lined stacks was actually less than that computed from available data on the damping of concrete. This verified the conclusions that the lining alone, either as designed or for a reasonable increase in thickness, would not provide sufficient damping to limit vibration to acceptable limints and that a suitable external damping system was necessary. The additional stiffness under dynamic loading contributed by the lining was surprisingly small.

Design of an Independent Self-Supporting Stack

For the extension to this station, it was necessary to erect two additional stacks of larger diameter, so arranged that a damping system would have been expensive and difficult to install. These new stacks were designed to be nonresonant with the eddy frequency for all wind velocities below 70 mph as computed from Eq 1. For maximum economy these stacks were tapered from top to bottom. The average diameter of the top 25 per cent was used in computing the eddy frequency since this contributes the greatest portion of the driving energy. These stacks are 224 ft-6 in. high with a base diameter of 27 ft-8 in. and a top diameter of 12 ft-8 in. inside the 2 in. gunite lining. They were placed in service in late 1952.

It might appear from the foregoing analyses that the use of a tapering section would automatically prevent formation of eddies since their frequency would be changing continuously with the stack diameter. Actually, present test data indicate that the width of the eddy trail and the Strouhal number are not rigidly fixed but can vary moderately. Consequently an appreciable length of a tapered stack could be acted upon by vortices of uniform frequency. Thus, even a tapered stack, if it had a natural frequency resonant with the frequency of eddy formation for say its upper quarter, could be excited to excessive amplitudes of vibration.

Conclusions

Steel stacks of many diameters and heights have been in common use for a long period of years throughout this country with its widely

varying terrain. Yet reports of serious stack vibration at moderate wind velocities were rare until recent years when increasing instances of this phenomena are being experienced.

It appears significant that until comparatively recent years most steel stacks were of riveted construction.

Review of published experimental data and theory about vortices indicates that formation of the vortices is primarily a shape function below Reynolds' number of approximately 200,000. However, for Reynolds' numbers in excess of about 1,000,000, formation of the vortices is in a condition of critical instability. This suggests that relatively small spoilers tripping only the boundary layer would protect stacks of conventional size and design against formation of periodic vortices. This may explain why riveted stacks, which are much rougher than butt welded stacks because of lap joints and rivet heads, have apparently been almost free from vortex-induced vibration. Unfortunately very little, if any, experimental work has been done at these very large Reynolds' numbers and consequently this hypothesis is not supported by experimental data. The possibility that small spoilers would be effective should be investigated fully.

However, until the effect of surface roughness on eddy formation is demonstrated, it is believed that increasing instances of phenomena similar to that described and analyzed in this paper, should lead designers of steel stacks, whether riveted or butt welded, to consider carefully the possibility that the forces due to eddy formation may be present.

Available information indicates that eddies form only in steady, nonturbulent air streams. Consequently sites located on flat terrain, or adjacent to large bodies of water offer favorable conditions for eddy formation with the attendant hazard of resonant vibration unless the stack is designed so as to be nonresonant for wind velocities below the critical range of eddy formation. Conversely sites in rugged terrain or where there are other adjacent structures provide less favorable conditions for eddy formation although the possibility should not be overlooked that an appreciable portion of the upper part of a tall stack may be above the turbulent air flow.

Available data indicate that stacks designed to be nonresonant with the frequency of eddies for wind velocities below 70 mph should not experience difficulty. Consideration must be given to both vibration as an elastic cantilever and vibration as an elastic ring. In the latter case the eddies will induce vibration at twice their own frequency.

The magnitude of lateral forces induced by eddy formation is uncertain. Reported experimental and theoretical values of C_L range from 0.65 to 1.71. Rigorous experimental determination of C_L at high Reynolds' numbers and laminar flow conditions for nonoscillating cylinders would be of considerable value in resolving this uncertainty.

Damping and additional stiffness from the Haydite-Lumnite gunite lining of about 2 in. thickness were surprisingly small. For the stacks described this amount of damping was insufficient to limit vibration to acceptable limits. The basic principles and criteria of design of a damping system which has proved satisfactory have been outlined.

The damping system described was installed on the stacks of the Moss Landing Steam Plant in the spring of 1950. At the time of this writing it had completed three years of service, during which the stacks were subjected to winds estimated to be of critical velocity a number of times. At no time has there been any observable vibration.

Acknowledgments

The plant was designed and constructed by Stone and Webster Engineering Corporation in collaboration with the Pacific Gas and Electric Company.

The test program described was suggested by and carried out in collaboration with and at the expense of the Pacific Gas and Electric Company with Mr. F. F. Mautz and Mr. W. F. Swiger in direct charge of the tests. At the time of the test program Mr. I. C. Steele, Director, ASCE, was Vice President in Charge of Engineering. Mr. Steele has been succeeded by Mr. Walter Dreyer, Member, ASCE, Mr. Carl Appelford, Member, ASCE, Supervising Civil Engineer, represented the Pacific Gas and Electric Company in matters relating to these stacks. Dr. J. P. Den Hartog served as Consultant on the design of the vibration damping system.

REFERENCES

1. Prandtl and Tietjens, "Applied Hydro and Aero Mechanics," Engineering Societies Monographs, McGraw-Hill.
2. Steinman, "Problems of Aerodynamic and Hydrodynamic Stability," Proceedings, University of Iowa, Third Hydraulic Conference 1946.
3. Reudy, "Vibrations of Power Lines in a Steady Wind," Canadian Journal of Research, October, 1935.
4. Pagon, "What Aerodynamics Can Teach the Civil Engineer," ENR, March 15, 1934, July 12, 1934.
5. Relf and Simmons, Aeronautical Research Committee Reports and Memoranda, Numbers 825, 917, 986 (British).
6. Den Hartog, "Mechanical Vibrations," Rev. 3, McGraw-Hill.
7. Goldstein, S., "Modern Developments in Fluid Mechanics," Vols. I and II, Oxford University Press.
8. Bleich and Teller, "Structural Damping in Suspension Bridges," Trans. ASCE, Vol. 117.
9. Muckenhoupt, Carl F., "Study of Concrete as a Material for Turbine Foundations," Unpublished Report.

TABLE 1
MOVEMENT OF STACKS

October 18, 1949

All measurements taken at top of stacks.

Time of Day, P.M.	Stack No. 3 — Movement at Top from Normal — North, In.	Stack No. 3 — Movement at Top from Normal — South, In.	Stack No. 3 — Total Movement, In.	Stack No. 2 — Movement at Top from Normal — North, In.	Stack No. 2 — Movement at Top from Normal — South, In.	Stack No. 2 — Total Movement, In.
1:00	14	16	30	15 3/4	14 1/4	30
2:00	16 3/4	14 1/4	31	12	13 1/2	25 1/2
3:00	17 1/2	15	32 1/2	13 1/2	15	28 1/2
4:00	10 3/4	9	19 3/4	8	9 1/2	17 1/2
5:00	No appreciable movement - Wind down					

EAST AND WEST MOVEMENT

At time of north and south movements both stacks had a practically uniform movement in the east and west directions as follows:

Stack No. 3 - Approximately 2 1/2 in. in each direction from normal, making total movement approximately 5 in.

Stack No. 2 - Approximately 2 in. in each direction from normal, making total movement approximately 4 in.

WIND DIRECTION AND VELOCITY

Wind direction - north of west.

Wind velocity estimated 30 to 40 mph at ground level.

TABLE 2A
VIBRATION DAMPING
STACK NO. 6 - UNLINED - JANUARY 6 AND 7, 1950
TRANSIT OBSERVATIONS

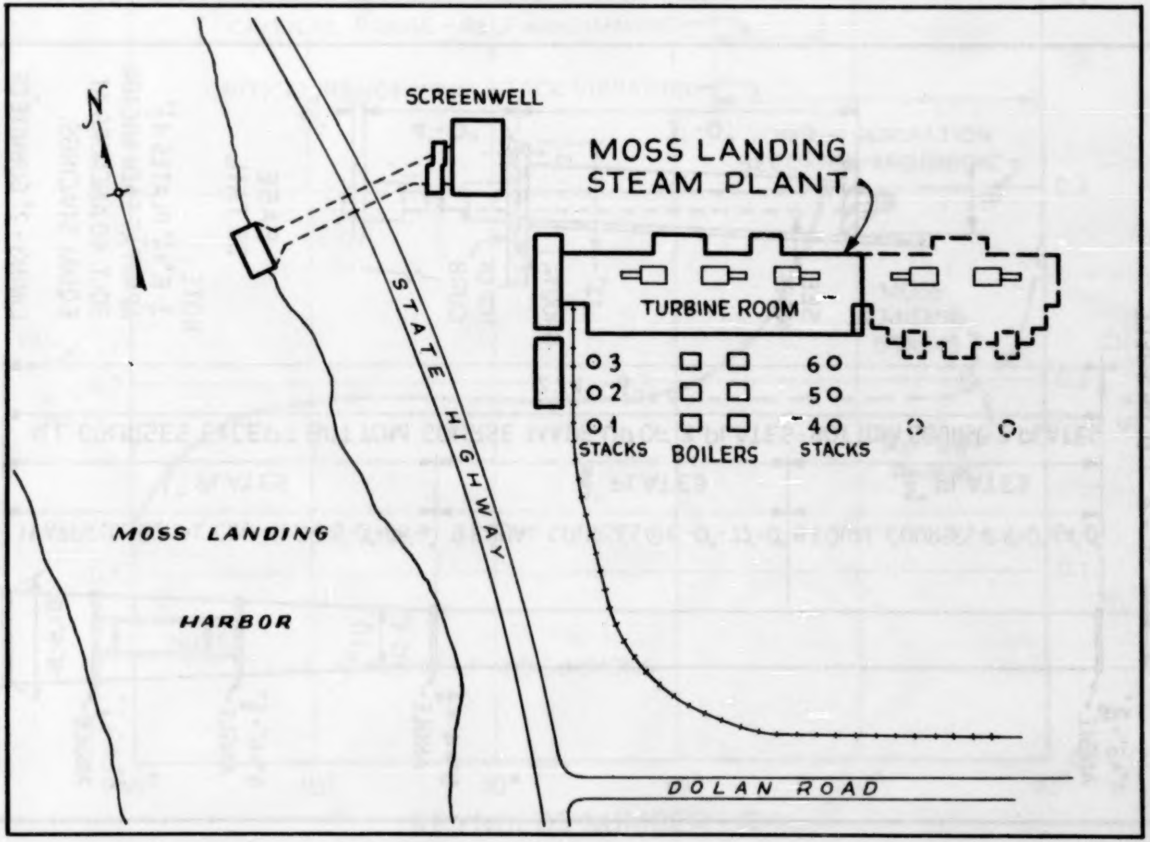
Run	Frequency, Cpm	Zero on Rod, Ft	Reading on Rod, Ft	Single Amplitude, Ft	Cycles from Release	Amplitude Ratios $\frac{Y_2}{Y_1}$	Increment of Cycles	Damping Decrement $= 1 - \left[\frac{Y_2}{Y_1}\right]^{\frac{1}{n}}$	
	Observations					Computations			
				North - South Vibration					
1	68	10.85	10.70	.15	17				
		10.87	10.80	.07	59	.467	42	.018	
		10.88	10.90	.02	96	.286	37	.033	
						.133	79		.025 mean value
2	68	10.85	10.70	.15	16				
		10.87	10.80	.07	55	.467	39	.019	
		10.87	10.90	.03	89	.428	34	.025	
						.200	73		.022 mean value
3	68	10.86	10.70	.16	13				
		10.87	10.80	.07	49	.438	36	.023	
		10.88	10.90	.02	76	.286	27	.045	
						.125	63		.032 mean value
				East - West Vibration					
4	66	8.01	7.70	.31	7				
		8.01	7.80	.21	12	.677	5	.075	
		8.01	7.90	.11	51	.524	39	.016	
						.355	44		.023 mean value
5	66	8.02	7.70	.32	6				
		8.02	7.80	.22	12	.687	6	.061	
		8.02	7.90	.12	41	.545	29	.021	
						.375	35		.028 mean value
6	66	8.00	7.70	.30	7				
		8.00	7.80	.20	16	.667	9	.044	
		8.00	7.90	.10	43	.500	27	.025	
						.333	36		.030 mean value
7	66	8.02	7.70	.32	7				
		8.02	7.80	.22	15	.687	8	.046	
		8.02	7.90	.12	42	.545	27	.022	
						.375	35		.028
									.027 average

TABLE 2B
VIBRATION DAMPING
STACK NO. 6 - LINED - APRIL 17, 1950
TRANSIT OBSERVATIONS

Observations						Computations			
Run	Frequency, Cpm	Zero on Rod, Ft	Reading on Rod, Ft	Single Amplitude, Ft	Cycles from Release	Amplitude Ratios $\frac{Y_2}{Y_1}$	Increment of Cycles	Damping Decrement $= 1-\left[\frac{Y_2}{Y_1}\right]^{\frac{1}{n}}$	
					North - South Vibration				
1	50	11.00	10.75	.25	3				
			10.80	.20	8	.800	5	.044	
			10.85	.15	15	.750	7	.040	
			10.90	.10	26	.667	11	.036	
			10.95	.05	48	.500	22	.031	
						.200	45		.035 mean value
2	50	11.00	10.75	.25	4				
			10.80	.20	9	.800	5	.044	
			10.85	.15	14	.750	5	.056	
			10.90	.10	26	.667	12	.033	
			10.95	.05	47	.500	21	.033	
						.200	43		.037 mean value
3	50	11.00	10.75	.25	3				
			10.80	.20	9	.800	6	.036	
			10.85	.15	15	.750	6	.047	
			10.90	.10	27	.667	12	.033	
			10.95	.05	45	.500	18	.038	
						.200	42		.038 mean value
					East - West Vibration				
4	48	8.00	7.75	.25	2				
			7.80	.20	5	.800	3	.072	
			7.85	.15	9	.750	4	.069	
			7.90	.10	19	.667	10	.040	
			7.95	.05	34	.500	15	.045	
						.200	32		.049 mean value
5	48	8.00	7.75	.25	3				
			7.80	.20	7	.800	4	.054	
			7.85	.15	11	.750	4	.069	
			7.90	.10	22	.667	11	.036	
			7.95	.05	38	.500	16	.042	
						.200	35		.045 mean value
6	48	8.00	7.75	.25	3				
			7.80	.20	7	.800	4	.054	
			7.85	.15	12	.750	5	.056	
			7.90	.10	22	.667	10	.040	.040 mean value
			7.95	.05	42	.500	20	.033	.041 average
						.200	39		

TABLE 2C
VIBRATION DAMPING
STACK NO. 6 - JANUARY AND APRIL, 1950
STRAIN GAGE RECORDS

Run	Frequency, Cpm	Amplitude, Micro, In.	Time from Release, Sec	Amplitude Ratio $\frac{Y_2}{Y_1}$	Increment of Time, Sec	Increment of Cycles	Damping Decrement $= 1 - \left[\frac{Y_2}{Y_1}\right]^{\frac{1}{n}}$	
				Unlined - East - West Vibration				
7	66	120	2					
		100	5	.833	3	3.3	.054	
		40	26					
		20	46	.500	20	22	.031	
				.167	44	48.4		.036 mean value
				Lined - North - South Vibration				
2	50	120	2					
		100	9	.833	7	5.83	.031	
		40	36.5					
		20	52	.500	15.5	12.9	.052	
				.167	50	41.7		.042 mean value
3	50	120	6					
		100	10.5	.833	4.5	3.8	.047	
		40	32					
		20	43.5	.500	11.5	9.58	.070	
				.167	37.5	31.3		.056 mean value
				East - West Vibration				
4	48	120	8.5					
		100	13.5	.833	5	4	.045	
		40	41					
		20	57.5	.500	16.5	13.2	.060	
				.167	49	39.2		.045 mean value
5	48	120	1					
		100	7	.833	6	4.8	.037	
		40	29					
		20	41	.500	12	9.6	.070	
				.167	40	32		.054 mean value
6	48	120	5.5					
		100	11	.833	5.5	4.4	.042	
		40	37.5					
		20	54.5	.500	17	13.6	.050	
				.167	49	39.2		.045 mean value
								.048 average for lined stack



SCREENWELL
MOSS LANDING
STEAM PLANT
TURBINE ROOM
3
2
1
STACKS
BOILERS
6
5
4
STACKS
STATE HIGHWAY
MOSS LANDING
HARBOR
DOLAN ROAD
N

Fig. 1

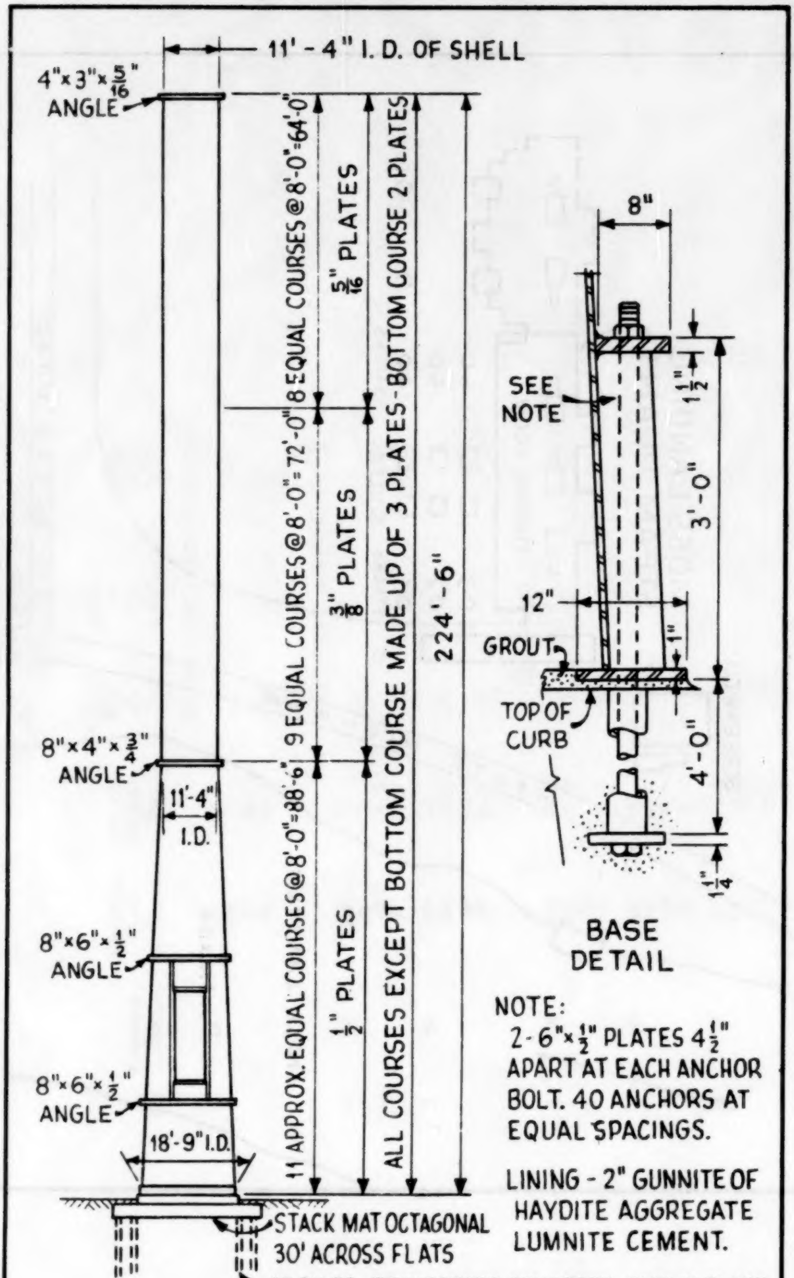

11' - 4" I. D. OF SHELL
4"x3"x5/16" ANGLE
8 EQUAL COURSES@8'-0"=64'-0"
5/16" PLATES
9 EQUAL COURSES@8'-0"=72'-0"
3/8" PLATES
11 APPROX. EQUAL COURSES@8'-0"=88'-6"
1/2" PLATES
ALL COURSES EXCEPT BOTTOM COURSE MADE UP OF 3 PLATES-BOTTOM COURSE 2 PLATES
224'-6"
8"x4"x3/4" ANGLE
11'-4" I.D.
8"x6"x1/2" ANGLE
8"x6"x1/2" ANGLE
18'-9" I.D.
STACK MAT OCTAGONAL
30' ACROSS FLATS
40 PILES-REINFORCED CONCRETE-CAST IN PLACE
TYPICAL ELEVATION
8"
SEE NOTE
1 1/2"
3'-0"
12"
1"
GROUT
TOP OF CURB
4'-0"
1 1/4"
BASE DETAIL
NOTE:
2-6"x1/2" PLATES 4 1/2" APART AT EACH ANCHOR BOLT. 40 ANCHORS AT EQUAL SPACINGS.
LINING - 2" GUNNITE OF HAYDITE AGGREGATE LUMNITE CEMENT.

Fig. 2

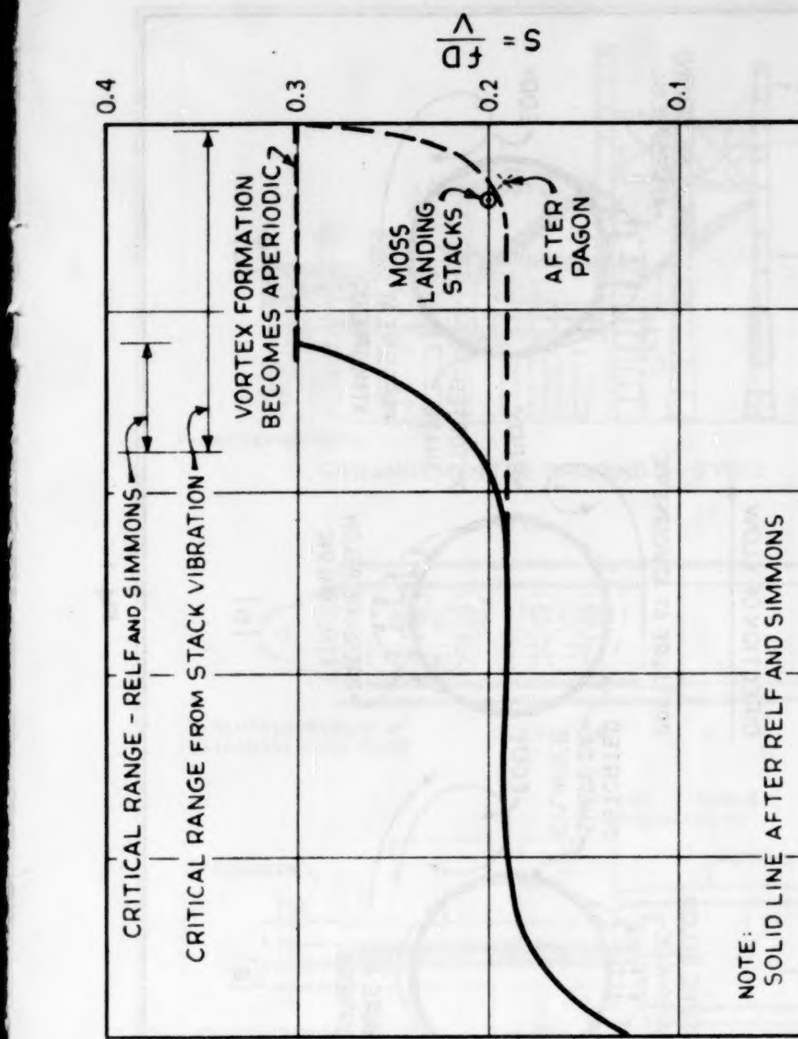

CRITICAL RANGE - RELF AND SIMMONS
CRITICAL RANGE FROM STACK VIBRATION
VORTEX FORMATION BECOMES APERIODIC
MOSS LANDING STACKS
AFTER PAGON
NOTE: SOLID LINE AFTER RELF AND SIMMONS
$S = \frac{fD}{V}$
0
0.1
0.2
0.3
0.4
10^2
10^3
10^4
10^5
10^6
10^7
REYNOLDS NUMBER - R

Fig. 3

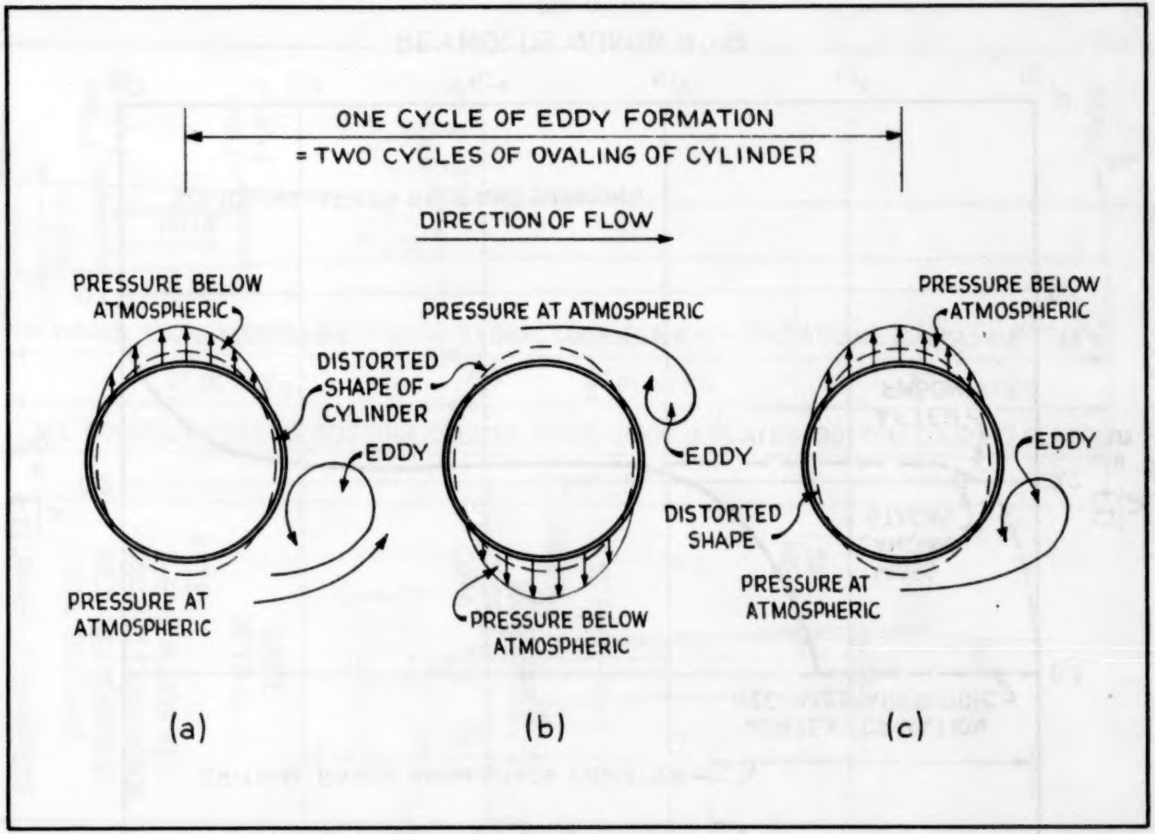

ONE CYCLE OF EDDY FORMATION
= TWO CYCLES OF OVALING OF CYLINDER
DIRECTION OF FLOW
PRESSURE BELOW ATMOSPHERIC
DISTORTED SHAPE OF CYLINDER
EDDY
PRESSURE AT ATMOSPHERIC
(a)
PRESSURE AT ATMOSPHERIC
EDDY
PRESSURE BELOW ATMOSPHERIC
(b)
PRESSURE BELOW ATMOSPHERIC
EDDY
DISTORTED SHAPE
PRESSURE AT ATMOSPHERIC
(c)

Fig. 4

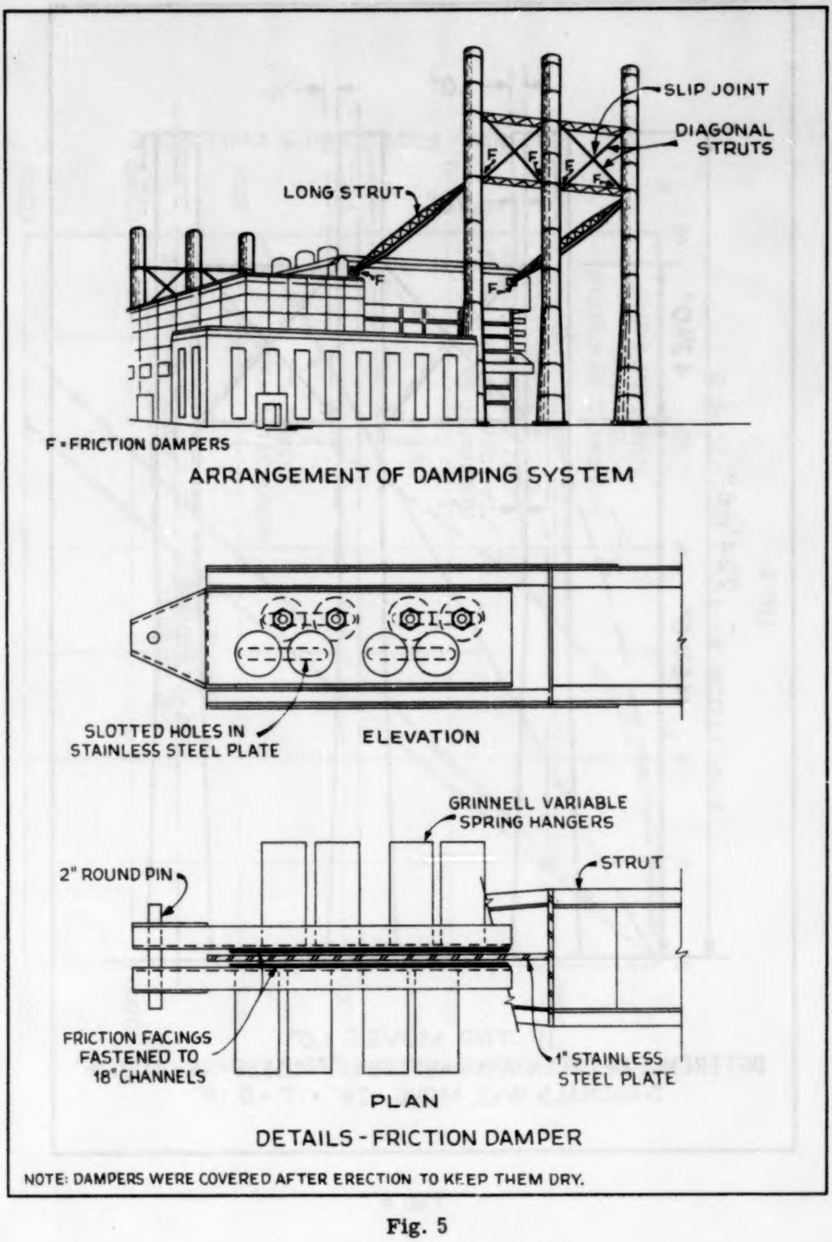

SLIP JOINT
DIAGONAL STRUTS
LONG STRUT
F
F = FRICTION DAMPERS
ARRANGEMENT OF DAMPING SYSTEM
SLOTTED HOLES IN STAINLESS STEEL PLATE
ELEVATION
GRINNELL VARIABLE SPRING HANGERS
2" ROUND PIN
STRUT
FRICTION FACINGS FASTENED TO 18" CHANNELS
1" STAINLESS STEEL PLATE
PLAN
DETAILS - FRICTION DAMPER
NOTE: DAMPERS WERE COVERED AFTER ERECTION TO KEEP THEM DRY.

Fig. 5

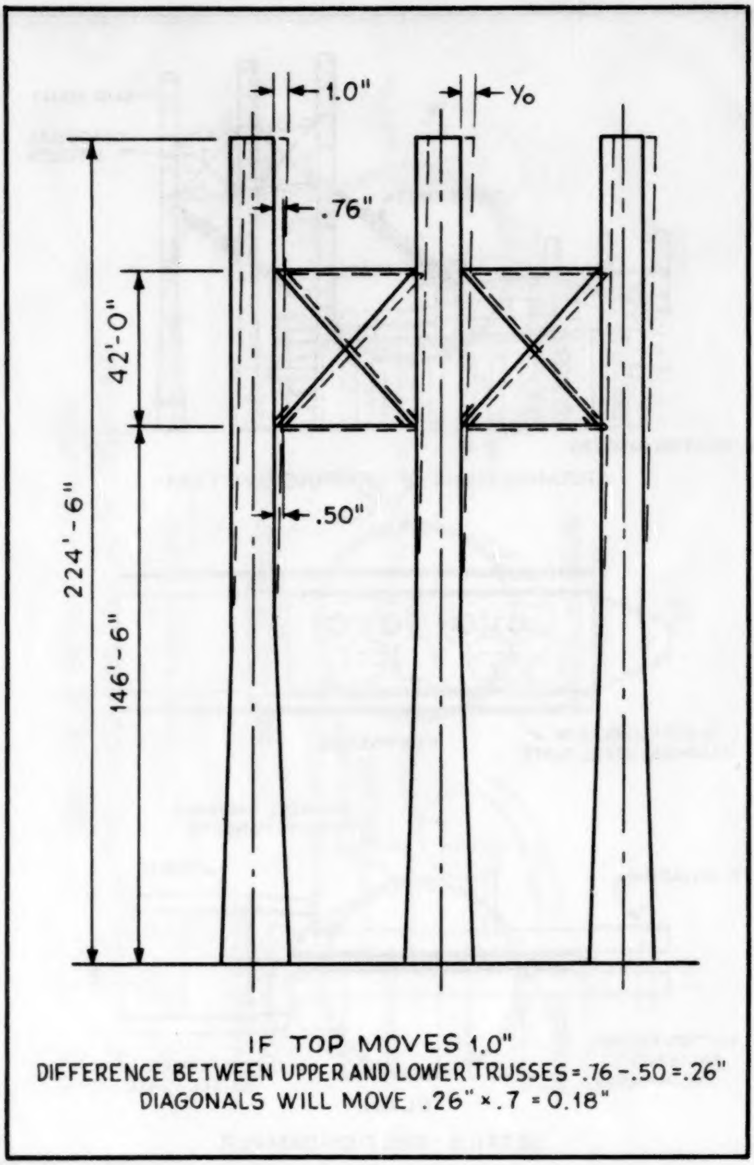
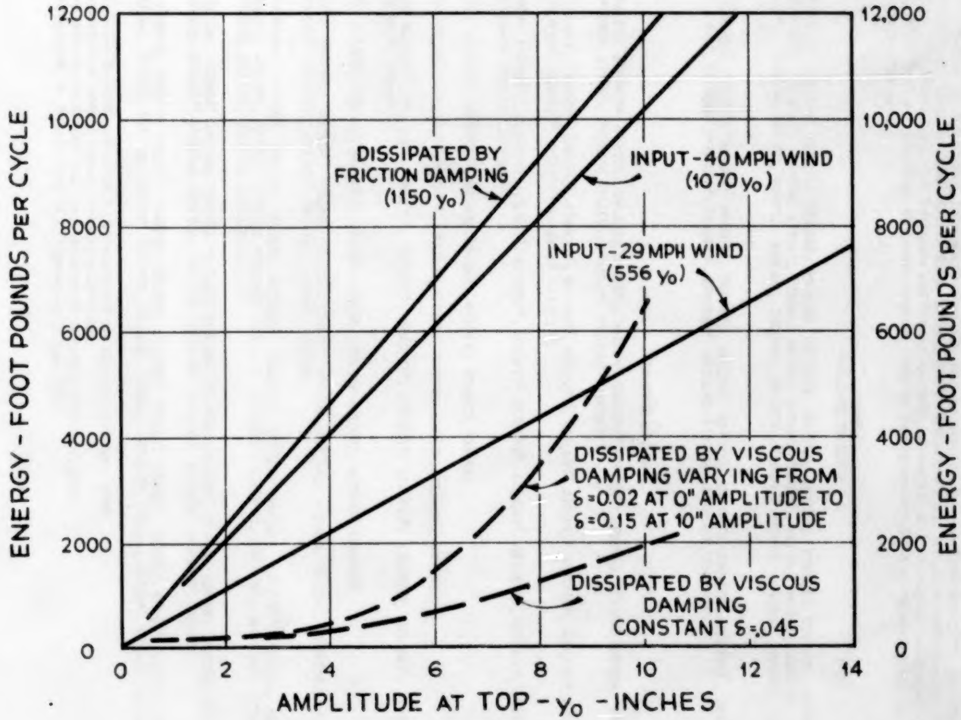

1.0"
Yo
.76"
42'-0"
224'-6"
.50"
146'-6"
IF TOP MOVES 1.0"
DIFFERENCE BETWEEN UPPER AND LOWER TRUSSES = .76 - .50 = .26"
DIAGONALS WILL MOVE .26" × .7 = 0.18"

Fig. 6



ENERGY - FOOT POUNDS PER CYCLE
12,000
10,000
8000
6000
4000
2000
0
DISSIPATED BY FRICTION DAMPING (1150 y_o)
INPUT - 40 MPH WIND (1070 y_o)
INPUT - 29 MPH WIND (556 y_o)
DISSIPATED BY VISCOUS DAMPING VARYING FROM δ=0.02 AT 0" AMPLITUDE TO δ=0.15 AT 10" AMPLITUDE
DISSIPATED BY VISCOUS DAMPING CONSTANT δ=.045
0
2
4
6
8
10
12
14
AMPLITUDE AT TOP - y_o - INCHES

Fig. 7

PROCEEDINGS-SEPARATES

The technical papers published in the past year are presented below. Technical-division sponsorship is indicated by an abbreviation at the end of each Separate Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways (WW) divisions. For titles and order coupons, refer to the appropriate issue of "Civil Engineering" or write for a cumulative price list.

VOLUME 79 (1953)

NOVEMBER: 321(ST), 322(ST), 323(SM), 324(SM), 325(SM), 326(SM), 327(SM), 328(SM), 329(HW), 330(EM)[a], 331(EM)[a], 332(EM)[a], 333(EM)[c], 334(EM), 335(SA), 336(SA), 337(SA), 338(SA), 339(SA), 340(SA), 341(SA), 342(CO), 343(ST), 344(ST), 345(ST), 346(IR), 347(IR), 348(CO), 349(ST), 350(HW), 351(HW), 352(SA), 353(SU), 354(HY), 355(PO), 356(CO), 357(HW), 358(HY).

DECEMBER: 359(AT), 360(SM), 361(HY), 362(HY), 363(SM), 364(HY), 365(HY), 366(HY), 367(SU)[c], 368(WW)[c], 369(IR), 370(AT)[c], 371(SM)[c], 372(CO)[c], 373(ST)[c], 374(EM)[c], 375(EM), 376(EM), 377(SA)[c], 378(PO)[c].

VOLUME 80 (1954)

JANUARY: 379(SM)[c], 380(HY), 381(HY), 382(HY), 383(HY), 384(HY)[c], 385(SM), 386(SM), 387(EM), 388(SA), 389(SU)[c], 390(HY), 391(IR)[c], 392(SA), 393(SU), 394(AT), 395(SA)[c], 396(EM)[c], 397(ST)[c].

FEBRUARY: 398(IR)[d], 399(SA)[d], 400(CO)[d], 401(SM)[c], 402(AT)[d], 403(AT)[d], 404(IR)[d], 405(PO)[d], 406(AT)[d], 407(SU)[d], 408(SU)[d], 409(WW)[d], 410(AT)[d], 411(SA)[d], 412(PO)[d], 413(HY)[d].

MARCH: 414(WW)[d], 415(SU)[d], 416(SM)[d], 417(SM)[d], 418(AT)[d], 419(SA)[d], 420(SA)[d], 421(AT)[d], 422(SA)[d], 423(CP)[d], 424(AT)[d], 425(SM)[d], 426(IR)[d], 427(WW)[d].

APRIL: 428(HY)[c], 429(EM)[c], 430(ST), 431(HY), 432(HY), 433(HY), 434(ST).

MAY: 435(SM), 436(CP)[c], 437(HY)[c], 438(HY), 439(HY), 440(ST), 441(ST), 442(SA), 443(SA).

JUNE: 444(SM)[e], 445(SM)[e], 446(ST)[e], 447(ST)[e], 448(ST)[e], 449(ST)[e], 450(ST)[e], 451(ST)[e], 452(SA)[e], 453(SA)[e], 454(SA)[e], 455(SA)[e], 456(SM)[e].

JULY: 457(AT), 458(AT), 459(AT)[c], 460(IR), 461(IR), 462(IR), 463(IR)[c], 464(PO), 465(PO)[c].

AUGUST: 466(HY), 467(HY), 468(ST), 469(ST), 470(ST), 471(SA), 472(SA), 473(SA), 474(SA), 475(SM), 476(SM), 477(SM), 478(SM)[c], 479(HY)[c], 480(ST)[c], 481(SA)[c], 482(HY), 483(HY).

SEPTEMBER: 484(ST), 485(ST), 486(ST), 487(CP)[c], 488(ST)[c], 489(HY), 490(HY), 491(HY)[c], 492(SA), 493(SA), 494(SA), 495(SA), 496(SA), 497(SA), 498(SA), 499(HW), 500(HW), 501(HW)[c], 502(WW), 503(WW), 504(WW)[c], 505(CO), 506(CO)[c], 507(CP), 508(CP), 509(CP), 510(CP), 511(CP).

OCTOBER: 512(SM), 513(SM), 514(SM), 515(SM), 516(SM), 517(PO), 518(SM)[c], 519(IR), 520(IR), 521(IR), 522(IR)[c], 523(AT)[c], 524(SU), 525(SU)[c], 526(EM), 527(EM), 528(EM), 529(EM), 530(EM)[c], 531(EM), 532(EM)[c], 533(PO).

NOVEMBER: 534(HY), 535(HY), 536(HY), 537(HY), 538(HY)[c], 539(ST), 540(ST), 541(ST), 542(ST), 543(ST), 544(ST), 545(SA), 546(SA), 547(SA), 548(SM), 549(SM), 550(SM), 551(SM), 552(SA), 553(SM)[c], 554(SA), 555(SA), 556(SA), 557(SA).

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a. Presented at the New York (N.Y.) Convention of the Society in October, 1953.
c. Discussion of several papers, grouped by Divisions.
d. Presented at the Atlanta (Ga.) Convention of the Society in February, 1954.
e. Presented at the Atlantic City (N.J.) Convention in June, 1954.

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PROCEEDINGS OF THE SOCIETY